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Accelerating innovation

The State of Charge

A GetFocus Report into the Future of Batteries

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By Jard van Ingen and Kacper Gorski

Viable Energy Storage Is at the Crux of the Energy Transition: EV Battery Chemistries Are a Key Driver to Adoption

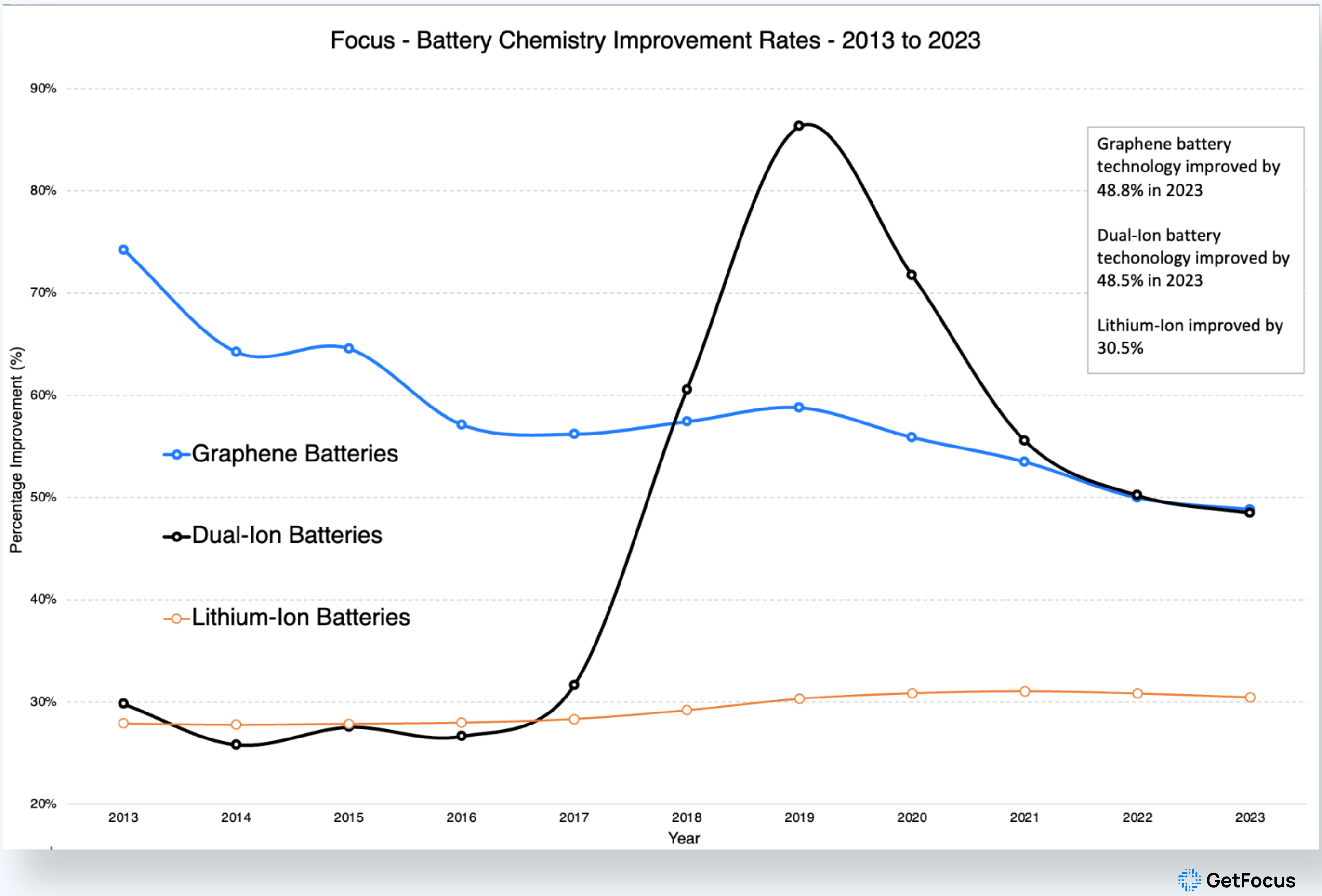

Figure 1 - The Battery Chemistry Improvement Rates shown for Graphene, Dual-Ion and Lithium-Ion over the past decade.

As the world accelerates towards the electrification of transport, the quest for superior battery chemistries becomes ever more important.

With over a dozen emerging chemistries in the EV space, how can you predict which will win? In this report we do exactly that and shine a light on the fastest-improving battery chemistries for EVs, forecast which are poised to dominate in the near and longer term, and which are more noise than actual signal.

Major Findings:

1. Lithium-based batteries remain the most viable in the near term: For the most established chemistries in EVs TRL 7 +), lithium-iron phosphate batteries are improving the fastest, but all lithium-based chemistries' improvement rates are similar. Meaning, that for now, Li-based chemistries are here to stay

2. Despite the hype, Solid-state Lithium underdelivers: Solid-state Li is improving at the same rate as more established lithium-based chemistries even though it is currently behind in its development. This makes it highly questionable whether solid-state Li could ever catch up and become the dominant chemistry.

3. Graphene and Dual-Ion are improving the fastest ~50% YoY Among emerging battery chemistries TRL < 5, innovation in Graphene and Dual-Ion batteries is significantly faster than currently dominant chemistries. Over 20 percentage points faster than Lithium Ion.

4. Graphene batteries expected by mid-2030s: Given the rate of improvement in Graphene production, we can expect that the cost of Graphene will reach Lithium cost parity of $11 per Kilo in the early to mid-2030s. It is, therefore, likely that Graphene batteries will become a reality around this time.

Introduction

Welcome to "The State of Charge", a new GetFocus report on cutting-edge electric vehicle EV battery technology.

The report dives into the world of battery chemistries, a critical component underpinning the growth of EVs.

To demystify the future of batteries, we've analyzed a range of promising chemistries, from the familiar lithium-ion variants to the nascent but exciting graphene, nanowire, and double ion technologies. Our goal is simple yet ambitious: to forecast which chemistries are not just buzzwords but real game-changers in powering the next generation of EVs.

We've rigorously evaluated technologies at different stages of development, employing Technology Readiness Levels TRLs) to gauge their maturity. From the advanced Lithium-Ion variants TRL 9 to the pioneering Graphene Batteries TRL 5, we forecast their potential.

We use the term TRL extensively throughout this report. For those not familiar with the term, we have included an explanation in the Appendix on page 22.
We've created this report to be a clear, concise guide in the often complex world of battery technology.

Whether you're an industry expert or an EV enthusiast, there are new insights for everyone.

Battery Chemistries Evaluated in this Report

- **Lithium-Nickel-Manganese-Cobalt Batteries TRL 9 and Lithium-Iron-Phosphate Batteries TRL 9:** These are the big players in today's EV market. TRL 9 because they're proven, reliable, and widely used. Lithium NMC batteries offer high energy density – a big plus for driving range, whereas LFP batteries aren't as energy-dense but they're safer and longer-lasting.

- **Sodium-Ion Batteries TRL 7:** Nipping at the heels of lithium-based batteries, these are cheaper and use more abundant materials. They're not as energy-dense, but for EVs, where cost and resource availability are key, they're a promising alternative.

- **Solid-State Lithium Batteries TRL 6 and Silicon-Anode Batteries TRL 7:** These are the up-and-comers. Solid-state batteries promise higher energy density and safety due to their solid electrolytes. Silicon anodes, meanwhile, can store more lithium, boosting capacity. Both are still in development but hold great potential for longer-range, safer EVs.

- **Lithium-Sulfur Batteries TRL 6:** With a higher theoretical energy density, these could one day outperform lithium-ion batteries. They're lighter too, which is great for EVs. But, they're still grappling with issues like short lifespan and poor performance at low temperatures.

- **Magnesium-Ion Batteries TRL 5, Graphene Batteries TRL 5, and Dual-Ion Batteries TRL 4:** These are mid-range in terms of development. Magnesium-ion offers the potential for higher energy density and safety. Graphene batteries, leveraging the super-conductivity of graphene, could charge faster and last longer. Dual-ion batteries are interesting for their potential cost-effectiveness and environmental friendliness.

- **Magnesium-Sulfur Batteries TRL 4, Nanowire Batteries TRL 4, and Potassium-Ion Batteries TRL 4:** These are the dark horses. They're less developed but hold promise. Magnesium-sulfur could offer high energy density and stability. Nanowire batteries might revolutionize longevity, surviving thousands of charge cycles. Potassium-ion stands out for its abundant materials and potential cost advantages.

In essence, for EVs, it's all about finding that sweet spot between energy density, safety, cost and sustainability. Each of these chemistries brings something unique to the table, and their development will shape the future of electric mobility. The key question is, however, which are actually progressing fast and which are over-hyped?

Battery Chemistry	TRL	Suitable for EV's?	Suitable for stationary storage?	Suitable for consumer electronics?
Lithium based				
Lithium-Sulfur	5	✓	✓	✗
Lithium-Nickel-Manganese-Cobalt	9	✓	✓	✓
Lithium-Iron-Phosphate	9	✓	✓	✓
Solid-State Lithium	6	✓	✓	✓
Lithium-Titanate	8	✗	✓	✗
Sodium-Based				
Sodium-Ion	7	✓	✓	✓
Sodium-Sulfur	9	✗	✓	✗
Sodium-Nickel-Chloride	8	✗	✓	✗
Metal-Air				
Sodium-Air	3	✗	✗	✗
Lithium-Air	4	✗	✗	✗
Magnesium-Air	2	✗	✗	✗
Aluminum-Air	4	✗	✗	✗
Zinc-Air	9	✗	✓	✓
Magnesium-Based				
Magnesium-Ion	4	✓	✓	✗
Magnesium-Sulfur	3	✓	✗	✗
Aluminum-Based				
Aluminum-Ion	3	✗	✗	✗
Zinc-Based				
Zinc-Bromine	7	✗	✓	✗
Nickel-Zinc	8	✗	✓	✓
Zinc-Manganese Dioxide	9	✗	✓	✓
Other Metal-Based				
Nickel-Metal-Hydride	9	✗	✓	✓
Nickel-Cadmium	9	✗	✓	✗
Nickel-Iron	6	✗	✓	✗
Nickel-Hydrogen	9	✗	✓	✗
Flow				
Redox Flow	8	✗	✓	✗
Solid-State Flow	3	✗	✓	✗
Hydrogen-Bromine Flow	5	✗	✓	✗
Vanadium Redox Flow	8	✗	✓	✗
Zinc-Bromine Flow	7	✗	✓	✗
All-iron flow	5	✗	✓	✗
Organic Redox Flow	4	✗	✓	✗
Organic				
Organic Radical	3	✗	✓	✓
Conducting Polymer	4	✗	✓	✓
Emerging Technologies				
Graphene	4	✓	✓	✓
Nanowire	4	✓	✓	✓
Liquid Metal	5	✗	✓	✗
Prussian Blue Analog	6	✗	✓	✗
Dual-Ion	4	✓	✓	✓
Potassium-Ion	4	✓	✓	✓
Aqueous Hybrid Ion	6	✗	✓	✓
Silicon-Anode	7	✓	✓	✓

Figure 2 - List of Battery Chemistries and their suitability for EVs

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Technology Forecasting: What Is It, and How Does It Work?

Inventors worldwide are constantly pushing the boundaries of technology, which in turn creates a massive data trail that can be mined for all sorts of insights.

The key thing here is that before new generations of technology hit the market, they are already described in the patent literature. If done well, patent data allows us to take a peek at the future.

At GetFocus, we developed a quantitative method to forecast the technological future based on metrics that can be identified in patent data. Using the latest advancements in AI technology, we have created a system that can estimate how rapidly any area of technology is improving.

Our method revolves around 3 key steps.

1. We identify every single patent that relates to an area of technology using AI. The resulting dataset represents the entire developmental history of an area of technology.
2. Once this data set is created we measure 2 key metrics.[1]

    a. Cycle Time - How many years it takes for a technology to produce a new generation of itself.

    b. Knowledge Flow - How significant of a step forward a new generation represents.

[1] Reach out to us if you are interested in learning more about our proprietary metrics.

3. Using the above metrics, we calculate the 'Technology Improvement Rate', which represents the average percentage (%) increase in performance per dollar that can be expected from an area of technology in one year.

By using the above methodology, technology improvement speeds can be accurately measured, and those speeds can be used to predict technological disruption well ahead of time.

If GetFocus and our method had been around in the past, one could have known that:

- Lithium-ion batteries would eventually become cheaper than combustion engines for vehicles by 1995,
- Digital photography would disrupt film by 1975,
- SSDs would become cheaper than HDDs by the early '80s, and the list goes on and on.

All in all, our forecasting method has been verified on more than 150 technological areas.

The Future of EV Battery Chemistries

Now that we've shared which battery chemistries are being discussed and how our forecasting method works, let's take a look at how quickly each chemistry is improving and what it means for the future.

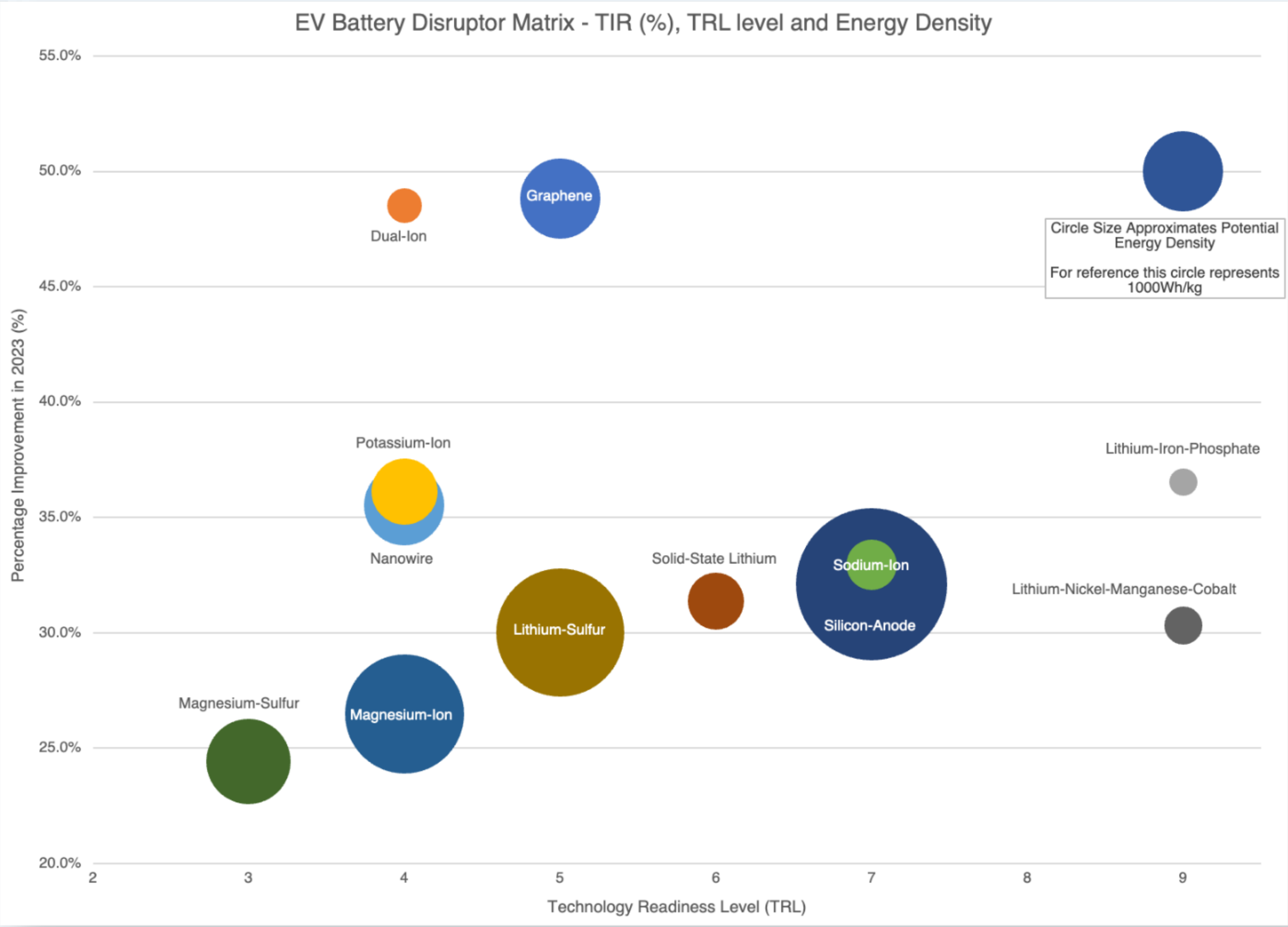

Figure 3 - The Disruptor Matrix shows all emerging battery chemistries, their estimated energy density, their improvement speeds, and TRLs.

Lithium-based chemistries - Using our methodology, we established that all lithium-based chemistries are improving at very similar speeds. The currently dominant chemistries, Lithium-Nickel-Manganese-Cobalt and Lithium-Iron-Phosphate, are improving at rates of 30% and 36% YoY.

Lithium sulfur batteries are improving at a rate of 30%, and silicon anode at 32%. This means that lithium sulfur and silicon anode technology cannot necessarily be seen as disruptive technologies. A key characteristic of disruptive technologies is that their improvement speeds are significantly and consistently higher than other areas of technology with which they compete. Lithium sulfur and silicon anode are thus better understood as continuing progress within the field of lithium-ion batteries.

Solid state: The much-hyped solid-state lithium battery — although very promising in theory, the Solid state's improvement speed sits at 31% YoY. This means that solid-state also cannot be seen as a disruptive technology. This does not paint the most promising picture for the future of solid state. Since the improvement speed of solid-state is not significantly or consistently higher than traditional lithium-ion chemistries, it means that solid-state lithium does not exhibit the characteristics of a disruptive technology.

Sodium ion: The same goes for sodium-ion batteries; the chemistry improves at a rate of +/- 33% per year, putting it within measurement error of Lithium-Iron-Phosphate batteries. This means we could see a transition towards Sodium-Ion from Lithium-Iron-Phosphate, but likely not in a disruptive manner.

Emerging battery chemistries: When looking at earlier-stage battery chemistries TRL 5 or lower), the picture becomes a lot more interesting. Graphene batteries are improving at a rate of **49%** YoY, and dual-ion batteries are improving at a rate of **48,5%** YoY. Other contenders in this area, Magnesium-Ion (**26%** YoY), Magnesium-sulfur 24.4% YoY), Nanowire batteries 35% YoY), and Potassium Ion batteries 36% YoY), are improving nowhere near as fast. Because the improvement speeds of graphene and dual-ion batteries are significantly and consistently higher than other competing battery chemistries, these can be considered disruptive.

Between dual-ion and graphene batteries, graphene batteries offer the highest potential as they offer incredible performance in theory. They promise high energy densities, increased cycle life, and fast charging. Their main downside is currently cost.

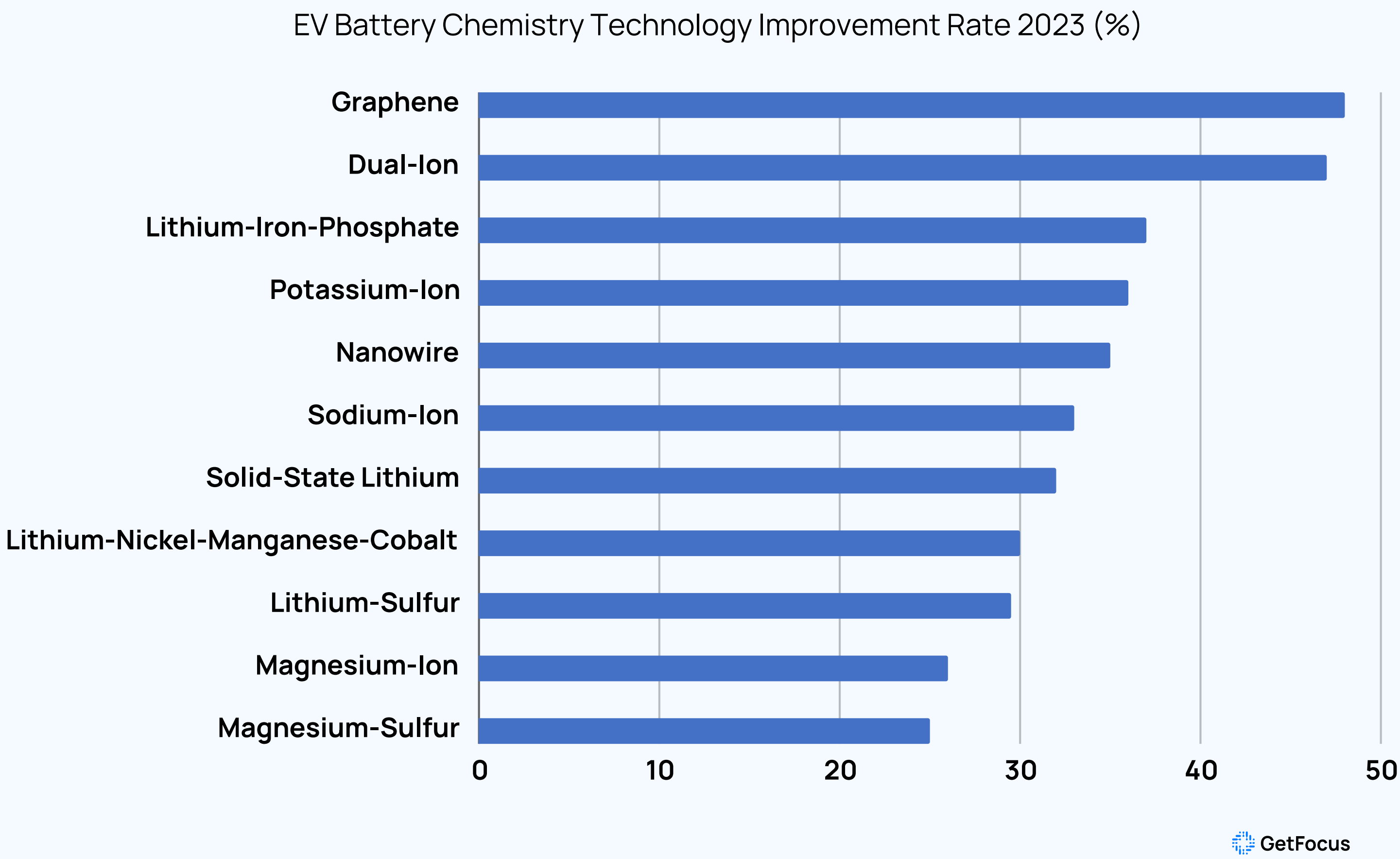

Figure 4 - Emerging battery chemistry improvement speeds in 2023, summarized.

So, how cheap does graphene production need to become to make graphene batteries a reality, and by when can this be expected?

In order to produce graphene batteries at an attractive price point, first, graphene production itself needs to become cheaper. The most recent article discussing graphene market prices we could find puts the market price at $200,000 per ton for high-quality graphene[2], which translates to $200 per kilo.

Calculating exactly how cheap graphene needs to become to make it attractive for incorporation into battery chemistries is challenging. However, a reasonable assumption would be that when prices fall to similar levels as where lithium is today, this threshold could be met.

Currently, lithium carbonate prices sit at around $16 per kilo, and analysts estimate this price could drop by an additional 30% in 2024[3], putting the expected price at around $11 per kilo.

When using GetFocus' forecasting method to estimate the improvement speed of graphene production, we find that it sits at 36.5% YoY. Assuming a current price of $200 per kilo, and a target price of $11 per kilo, we forecast the following:

2 https://bigthink.com/the-present/flash-graphene/

3 https://www.reuters.com/markets/commodities/china-lithium-price-poised-further-decline-2024-analysts-20231201/

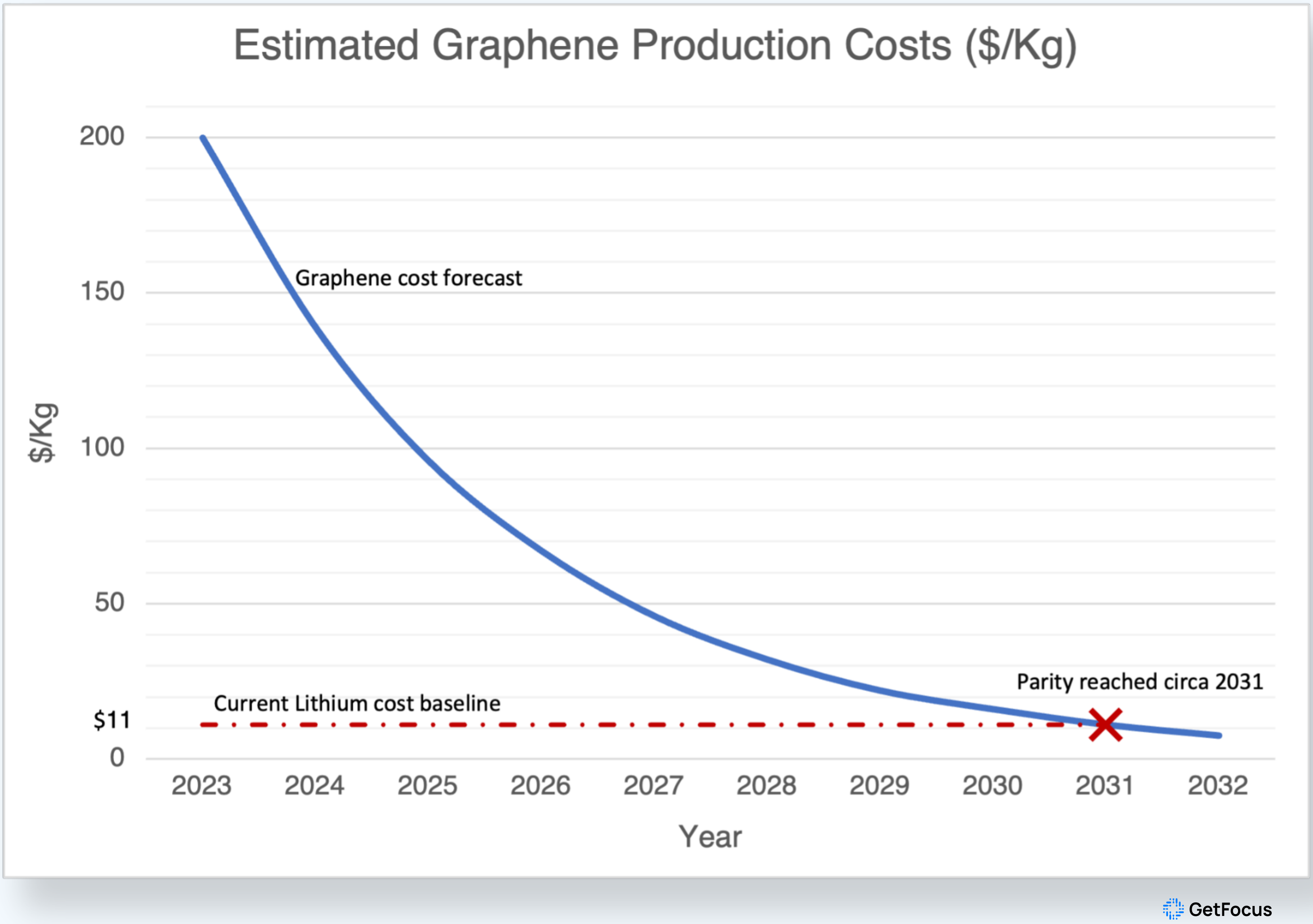

Figure 5 - Graphene price forecast versus 2024 estimated lithium price

It can be expected that graphene production will become cheap enough to find its way into battery chemistries by around 2031. **If there is one battery technology to keep an eye on, it is graphene.**

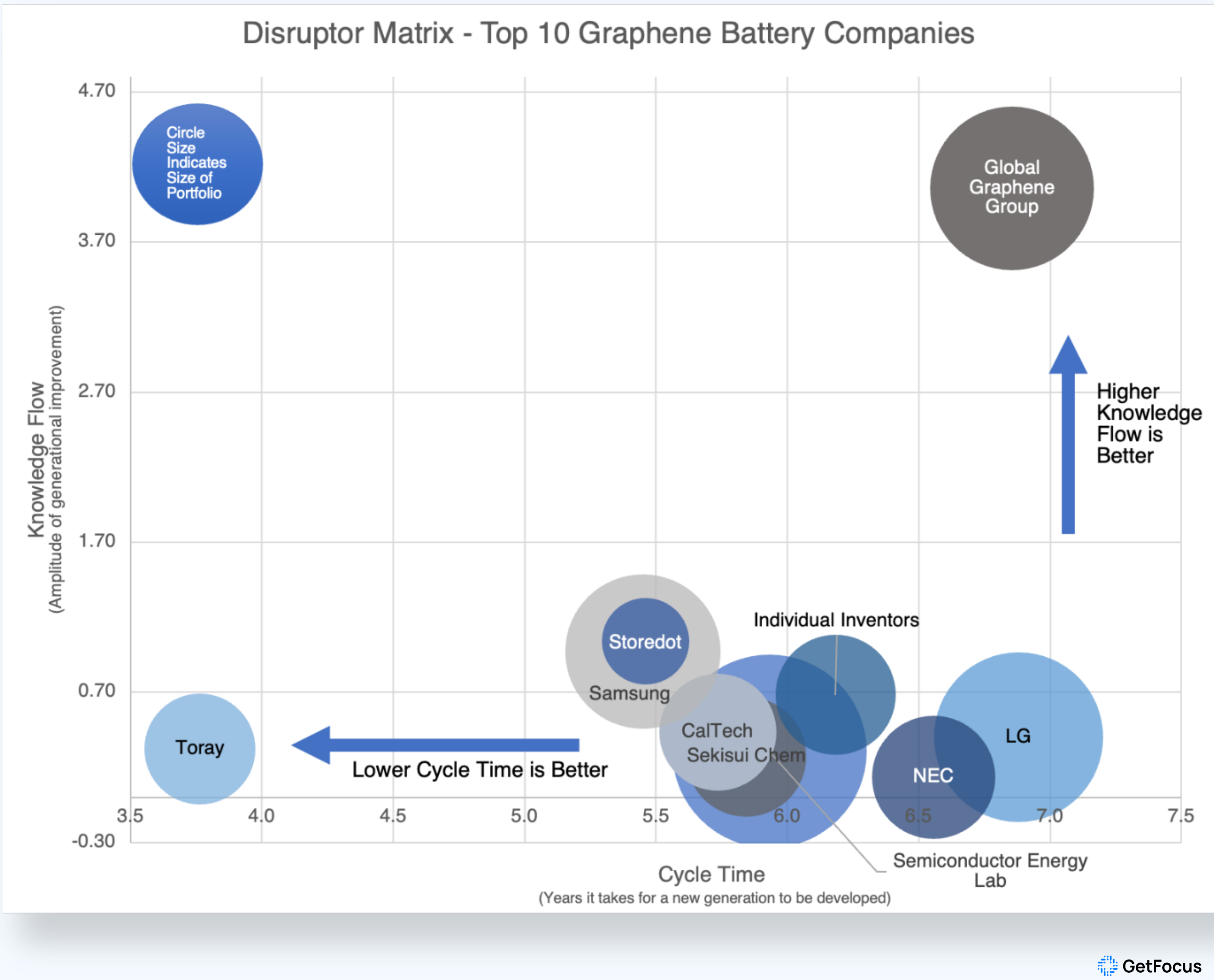

Figure 6 - Graphene battery company disruptor matrix

Now that we know how promising the future of Graphene batteries is, there is time to prepare by finding the partners for your supply chain, spin-up R&D centers and work with research institutions or conduct the necessary M&A activities to ensure smooth technology adoption and ultimately, facilitate a better product for the consumer.

In the technology landscape, we have identified over 300 organizations actively working on Graphene battery technology. Figure 6 depicts our evaluation of the top 10 companies that are best positioned to disrupt the current battery market with Graphene.

- **Global Graphene Group**, which we rank as the most impactful company working in this field, has announced its subsidiary, **Honeycomb Battery Company**[4], is entering a combination agreement with Nubia Brand International Corp. This deal involves Nubia issuing 70 million shares of its common stock, valued at $700 million. The agreement is set to enhance Honeycomb's manufacturing and research capabilities, primarily focusing on advanced battery technology for electric vehicles.

- **StoreDot**, the only start-up in the top 10, has made significant progress in 2023. They are on track for the mass production readiness of their '100in5' battery cells in 2024. These cells are designed to deliver at least 100 miles of range in just 5 minutes of charging. In addition to collaborating with **Polestar** on the world's first 10-minute EV charging demo for early 2024, StoreDot has formed landmark agreements with strategic partners such as Volvo Cars, VinFast, and FlexINIGate. Their batteries' quality was validated after testing by 15 leading global OEMs, showing no degradation even after 1,000 consecutive XFC (Extreme Fast Charging) cycles.[5]

- **Toray Industries,** which we've identified as the fastest iterating player (lowest Cycle Time), has made significant advancements in the field of graphene batteries. Developing an ultra-thin graphene dispersion solution characterized by excellent fluidity and electrical and thermal conductivity. This solution is particularly beneficial for applications such as battery and wiring materials.

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4 https://www.globenewswire.com/news-release/2023/02/16/2609465/0/en/Global-Graphene-Group-s-Honeycomb-Battery-Company-Announces-Business-Combination-Agreement-with-Nasdaq-Listed-Nubia-Brand-International-Corp.html

5 https://finance.yahoo.com/news/storedot-ends-2023-worlds-leading-090000122.html?guccounter=1

Toray's innovation lies in its ability to create very thin, high-quality graphene from inexpensive graphite materials.[6] Their unique dispersion technology allows for the control of viscosity, making it easier to handle and apply the solution without dilution. This technology is expected to significantly improve the performance of batteries, offering 50% better battery life than traditional carbon nanotubes used as conductive agents.

Conclusion

Traditional lithium-based batteries continue to maintain their stronghold on the EV market for the near term, but alternative chemistries like sodium-ion may present an eco-friendly and cost-effective option.

It is the emerging technologies such as graphene and dual-ion batteries, however, that are showing disruptive improvement speeds and could redefine the future landscape of EV energy sources by offering significant advancements in energy density, safety and environmental sustainability.

As we approach the mid-2030s, graphene batteries, in particular, will emerge as a strong contender for becoming the next big leap in EV battery technology with expected dramatic drops in graphene production costs. Industry players and enthusiasts should keep a close watch on these developments as they promise not only to enhance electric vehicle performance but also to contribute to the broader goals of energy efficiency and reducing carbon footprints.

Our report provides a comprehensive look into these future trends, supporting businesses and consumers alike in making informed decisions about the rapidly evolving world of battery technology.

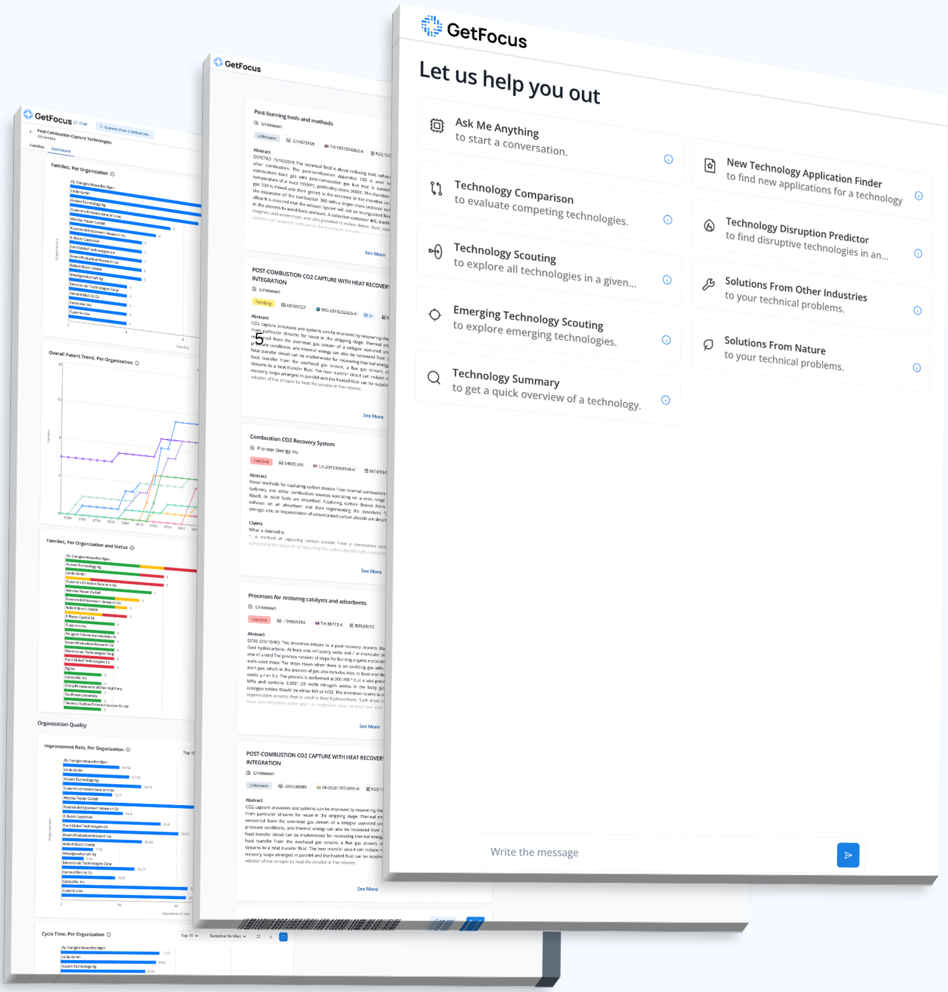
By continuing to focus on innovation and leveraging strategic insights, we can navigate towards a more electrified and sustainable future with confidence.

[6] https://www.toray.com/global/news/details/20210308000606.html

About GetFocus

GetFocus built the world's first platform that can reliably forecast the technological future using advanced AI technologies. It turns out that winning technologies show clear and measurable patterns. We extract these patterns from patent data and make them available in a SaaS tool so businesses can make strategic investments in the right emerging technologies.

Next to forecasting, we enable R&D leaders to get up to speed on new technologies 100X faster by giving them AI-powered tools for trend scouting, technology summaries, and technology deep dives. The entire platform works through natural language and is very easy to use.



Method:

GetFocus orchestrates 3 types of AI to facilitate technology scouting, landscaping, and forecasting.

1

Large Language Models

Used to scout emerging technology areas in any context.

2

Vector search

Used to gather the relevant invention data within each technological area. This dataset is then refined to make sure it accurately represents a technological area.

3

Multivariate regression

Based on invention data and empirically measured technological improvement data is used to forecast technology improvement rates.

Our approach is inspired by research from the Massachusetts Institute of Technology MIT.

Estimating technological improvement speeds is useful because, historically speaking, the fastest improving technology among a set of competing technologies always becomes the dominant solution.

This takes into account the age, industry, application, and “popularity” of the technology and is true for every historical case of technology disruption that has ever been studied.

The improvement speed for each technology is derived from the citation metadata of the inventions associated with each technological landscape.

The Technology Improvement Rate TIR is a compound metric of Cycle Time (how many years does it take for a new generation of a technology to come out) and Knowledge Flow (how large each generational improvement is).

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About the Authors:

Jard van Ingen,
CEO and co-founder of GetFocus

As CEO and co-founder of GetFocus, the world's first predictive AI analysis platform that accurately and reliably predicts the technological future based on global patent data, Jard van Ingen is responsible for leading and executing the company's vision and strategy, product development at large, and overseeing global sales and strategic partnerships. Energetic and hands-on, Jard is all about making complex tech trends in innovation easy to understand so R&D leaders can navigate the rapidly changing tech world.

Jard holds a master's degree in Intellectual Capital Management and Entrepreneurship from the University of Gothenburg in Sweden and a bachelor's degree in Business and Managerial Economics from the Amsterdam University of Applied Sciences.

Kacper Gorski
Head of Operations

A Physicist by training with a focus on material science, Kacper has always been motivated by sharing technology stories through data at the bleeding edge of innovation.

After 8 years in IP at PatSnap and LexisNexis Cipher, Kacper honed his skills in Data Analysis, AI, Research and Risk Consulting. Kacper joined GetFocus and heads up the Research team to accelerate the future of innovation by leveraging IP through sensible AI.

Appendix - What Are TRLs and How Are They Defined?

The Technology Readiness Scale TRL, originally developed by NASA, is widely used across industries to assess the development stage of technologies, especially in fields like aerospace, defense, and energy. The scale ranges from 1 to 9, with each level representing a different stage of technology development.

TRL 1 – Basic Principles Observed: This is the most preliminary stage. It involves the basic observation of scientific principles and the identification of the concept. Theoretical research and scientific study are conducted to support the feasibility of the ideas.

TRL 2 – Technology Concept Formulated: At this stage, the basic technology concepts and applications are formulated. Initial theoretical and experimental proof of concept is developed. This is more about conceptualizing how the technology might work.

TRL 3 – Experimental Proof of Concept: This stage involves active experimentation to validate the theoretical predictions. Laboratory experiments are conducted to physically demonstrate the feasibility of the concepts.

TRL 4 – Technology Validated in Lab: The technology is further developed and validated in a laboratory environment. This includes bench-scale or small-scale testing, typically under simulated or partially simulated environments.

TRL 5 – Technology Validated in Relevant Environment: The technology is demonstrated in an environment that closely represents the real-world application. This stage is crucial for understanding how the technology functions outside of the controlled lab setting.

TRL 6 – Technology Demonstrated in Relevant Environment: A significant step where the technology model or prototype is tested in a relevant environment. This stage demonstrates the technology's performance in scenarios that closely mimic the operational environment.

TRL 7 – Technology Demonstrated in Operational Environment: The prototype is now demonstrated in an operational environment. This is a full-scale, realistic test, showing that the technology works reliably in the intended environment.

TRL 8 – Technology Proven Ready for Production: The technology has been proven to work and is ready for commercial production. It has passed all final tests and validations and is considered mature and reliable.

TRL 9 – Actual Technology Proven Through Successful Operations: The final stage is where the technology is not only proven but also has been actually deployed and used successfully in its final form in real-world operations.